

Story of a journey Rutherford to the Large Hadron Collider and onwards..

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Abstract

In this article, I set out arguments why the Large Hadron Collider (LHC) : the machine and the experiments with it, are a watershed for particle physics. I give a historical perspective of the essential link between development of particle accelerators and that in our knowledge of the laws governing interactions among the fundamental particles, showing how this journey has reached destination LHC. I explain how the decisions for the LHC design; the energy and number of particles in the beam, were arrived at. I will end by discussing the LHC physics agenda and the time line in which the particle physicists hope to achieve it.

1 Introduction

More than a year and half ago the ‘Large Hadron Collider’ (LHC), came into limelight, due to the spectacular show of its start up, the equally spectacular accident soon after and also for the doomsday stories that circulated around its start up. The accident put it out of action for a while. Now the necessary repairs done, the damaged pieces replaced, the machine has taken the first tentative steps in its life beginning on November 23, 2009. Having set a world record for the proton beam energy, of 1180 GeV, on November 30, 2009, it went back to the lower beam energy of 450 GeV per beam and ran for about two weeks in the collision mode. The detectors collected data, corresponding to a few hundred thousand pp collision events,¹ over this period confirming that their intricate machinery performed as it should and can measure the properties of the myriad of particles produced in these collisions, to the desired accuracy. After a winter shut down (partially caused by the escalation in energy costs due to the increased energy demands otherwise in winter) the machine started working again on 20 th February 2010. After circulating proton beams at the higher energy of 3.5 TeV since 19th March 2010, finally collisions at the total centre of mass energy of 7 TeV happened on the 30th March 2010; albeit this was still only half the originally planned energy and with 10 times less number

¹At full throttle LHC detectors will have to deal with over 600 million proton collisions per second.

of particles per bunch than initially foreseen for the restart. The decision to do so being taken, in the words of CERN Director General, Rolf Heuer, as a ‘prudent step by step approach’ as ‘the LHC is not a turnkey project’. Papers, presenting results from the December runs have already been published in research journals [1–3] and more have been submitted already from the collisions in March [4], with thousands of authors signing them. Particle physicists: experimentalists and theorists alike, are waiting now with baited breath, just as they have been for more than a decade now, for the results which will come out of these collisions. I write these lines from CERN, where even in the cafeteria now the television screens display information about the LHC machine operation!

While the rest of the world came to know of this extremely complicated endeavor only about a year and half ago, for the worldwide community of particle physicists (which incidentally developed the World Wide Web (WWW) two decades ago), this is perhaps the concluding chapter of the long running love story between the world of fundamental constituents of matter and that of the accelerators which get these particles to move at the speed of light. In this article I discuss why thousands of particle physicists the world over, together, have embarked upon this truly mammoth project and worked on it over three decades. I wish to highlight what we all hope to learn from doing experiments with this unique machine. The construction of this accelerator and that of the equally huge and complex detectors, by itself, has been an amazing and utterly impressive engineering achievement. To appreciate the scope of this achievement by accelerator physicists and engineers, from CERN and the rest of the world, including India, we should follow a story which began perhaps a century ago. It is also a story of a development of a methodology of the ‘mega’ science projects that the high energy physicists have developed.

The development of our knowledge of the laws of physics that function at the heart of the matter has been very closely interlinked with that of the accelerators. It may be said that the discovery of the first fundamental particle, the electron, by J.J. Thompson in 1897 was due to the first ‘accelerator: a cathode ray tube’, which accelerated electrons. The partnership between accelerators and particle physicists on this adventure has continued through the century. The legendary physicist Lord Rutherford, who discovered existence of a nucleus inside an atom using the alpha particles emitted by the radioactive nuclei, had said, dreaming about high energy particles to uncover nature’s secret “It has long been my ambition to have available a copious supply of atoms and electrons which have energies transcending those of the alpha, beta particles from the radioactive bodies”. His dream was full filled by Walton and Cockroft in the Cavendish Laboratory. The target of energy (MeV : Million electron volt) to which the particles needed to be accelerated, was set by Gamow’s theory of radioactive decay. This gave the height of Coulomb barrier to α emission in a nucleus and hence indicated the energy level

to which particles need to be accelerated for possible artificial radioactivity: the aim of Rutherford's experiments at that time. Since then the nuclear/particle physicists have been setting the bar higher and higher and accelerator physicists have been clearing it with regularity, like Sergey Bubka or Yelena Isinbayeva.

Compared to the early machine by Walton and Cockroft which fitted in a room or the early cyclotron by Lawrence and Livingstone which was only 11 inches in diameter, today's machines are truly gigantic. Further, the energies to which these machines accelerate the particles are higher by many orders of magnitude. The Tevatron at the Fermi National Accelerator Laboratory (FNAL) in Batavia in USA, held the record for accelerating protons to about a thousand times its rest mass energy ~ 1000 GeV or 1 TeV, corresponding to a total collision energy of 2000 GeV; a feat that the LHC eclipsed by first reaching a total collision energy of 2360 GeV and then 7000 GeV, as said before.

Acceleration of particles to these high energies is not achieved by the use of electrostatic force alone, but has to be by a judicious combination of the alternating electric fields and magnetic fields as is done in the more sophisticated cyclotron. Lawrence's first model, costing only US \$ 25 in 1931, used 2000 volts of electricity but produced protons with energy 80,000 electron volts. Magnetic fields are not only required to facilitate this acceleration of particles, but later also to keep them on a tight leash and steer the beam around its path as a tight bunch, without allowing them to spread apart. All this beam optics requires careful designing of magnetic fields, with very precise spatial distribution. Thus an accelerator physicist has to deliver a beam of particles accelerated to speeds close to that of light², containing a large number of particles ($\sim 10^{11}$ or more for the LHC at the nominal design) and with a small transverse size (a few μm at the collision point for the LHC). The beam has to maintain this size while the particles are transported across the long periphery of the machine (27km for the LHC ring), many times ($\sim 10^6$) over. Clearly this whole exercise poses extreme technological challenges and requires fine engineering.³

The decisions about the type of particles which should collide and the energies to which they should be accelerated, are guided crucially by our current theoretical understanding of fundamental particles and the interactions among them. This interplay of different sub-disciplines in the field of high energy physics is seen in the citation of the 1984 Nobel prize for physics which was shared by the experimental physicist Carlo Rubbia and the accelerator physicist Simon Van Der Meer "for their decisive contributions to the large project, which led to the discovery of the field particles W and

²for the case of 1 TeV protons mentioned above $v = 0.9999995 \times c$

³Note that it is not enough to make these beams of particles of high energy. It has to be accompanied by the construction of equally intricate detectors to 'detect' traces of particles produced in these collisions.

Z, communicators of weak interaction”. The large project mentioned in the citation was the Super proton-antiproton Synchrotron: the $S\bar{p}\bar{p}S$ which started operation at CERN in Geneva, Switzerland in 1983. This project involved converting the proton-proton collider which had been commissioned in 1976, into a proton-antiproton collider. The need to do so was indicated by theorists’ calculations which showed that given the limited energy to which the proton could be accelerated using the then available technology, the feat of producing the W/Z bosons in the laboratory, could be achieved only if one collided protons on *antiprotons* and that too in large numbers. This prediction was made using the then established Glashow-Weinberg-Salam model (put forward in 1968) which gave a unified description of the electromagnetic and weak interactions⁴ and with the knowledge of the momentum fraction of the proton carried by some of its constituents, the quarks and the anti quarks⁵. Simon Van Der Meer’s discovery of ‘stochastic cooling’ made it possible to produce tightly focused antiproton beams whereas Rubbia’s vision and drive made it possible for the project to be realised. Already this little discussion tells a lot of things about the current state of play in high energy physics, including the need for ‘project’ leaders to take these big projects from conception to realisation and the very high level of collaboration necessary, not just among the large number of experimentalists working together on one single experiment, not just among them and the theorists, but also among these two groups and the accelerator physicists. The particle physics community has been grappling for decades and with reasonable success, with running these mammoth collaborative projects and at the same time keep individuality, the basis of all progress, alive!

In this narration, I will first try to explain why LHC: the machine and the experiments with it, are a watershed for particle physics. I will then sketch the essential link between the development of particle accelerators and that in our knowledge of the laws governing the interactions among the fundamental particles, showing how this journey has reached destination LHC. After this I briefly describe how the high energy physics experiments of past few decades have provided important pointers to the physicists who are hunting for the Higgs boson and other new particles/physics at the LHC. This discussion will then help us understand how the decisions for the LHC design; the energy and number of particles in the beam, were arrived at. I will then end by telling about the LHC physics agenda and the time line in which the particle physicists hope to achieve it.

⁴The inventors of this theory called the EW theory, had already been awarded the Nobel prize in 1979.

⁵Friedman, Kendall and Taylor, who in 1968 performed the first experiment which gave indication of the quark structure of the proton, received Nobel prize for physics in 1990.

2 The story of LHC

2.1 LHC: a watershed experiment

As we go along we will try to understand, why particle physicists believe that, at least one, as yet undiscovered particle, must exist out there and the LHC will see it. Independent of whether this turns out to be the Higgs boson with the properties predicted by the corresponding theory, we also expect existence of even more particles/interactions which LHC will be in a good position to find should they exist. One thing is for sure. LHC : the machine and the experiment, is going to be a watershed for the subject of fundamental particle physics. Particle Physics will never be the same, independent of what the experiments find. LHC is now the doorstep and the day of reckoning at hand. We expect the LHC to find the last missing piece of the standard model, the Higgs boson. We expect much more. We believe LHC will also point the way ahead (or even to a dead end?), help unravel the deepest secrets of nature and space time. Hence it is a watershed experiment.

To appreciate why this is so, it is important to understand the current state of play in the subject. The normal course through which science progresses is well known to all of us. Barring the work of geniuses like Einstein, normally, existing theory and observed phenomena which are unexplained in the framework of that theory, lead to new theoretical developments. This then leads to predictions, which then get tested in experiments. However, in the subject of High Energy Physics (HEP) one is in a very strange situation. We have a theory, called Standard Model (SM) of particle physics, which works so well that there seems to be almost no unexplained phenomena.(See Box-I, for some details of the SM.) Various new theoretical developments have taken place only by the demands made by the community on the properties that the mathematical theory ought to have for it to be a satisfactory description of the fundamental interactions. One example of a very simple demand is called unitarity: which very simplistically stated means that probabilities for different events are bounded by unity, as they always must be. Some of the theoretical developments beyond the SM (BSM) have also come by demanding that some features, such as the values of the masses that different particles have, should be understood from first principles in the theory. For example, in the SM, we have such a first principle understanding why the rest mass of the photon is zero. All the efforts to find *direct* proof for any of these new ideas (Supersymmetry, additional compact dimensions of space [5] to name a few), in the various particle physics experiments and/or to look for their implications in cosmology/astrophysical situations, have yielded, so far, negative results. In other words, we seem to have found a ‘perfect’ theoretical description of fundamental constituents of all the matter and interactions among them,

barring a ‘direct’ verification of one last ‘piece’ of the puzzle, the Higgs boson.

On the one hand, the particle physics community has strong theoretical reasons that there is new physics at the TeV scale, while on the other, the experimental evidence for its ‘need’ is only in the form of tantalising ‘indications’ such as non-zero masses for the neutrinos, or the dark-matter in the Universe etc. It should be emphasized here, that the track record of particle physicists is pretty good so far in this context and theoretical developments based on demands of aesthetics alone have been fruitful at getting at the root of some of the very fundamental questions about laws of nature. But, admittedly, the time gap between theory and experiment has never been so big as it is at present. We are still awaiting the final experimental verification of a theoretical advancement made in 1964.

One direction in which progress can come is by increasing the available energy at which particle interactions are studied. There are solid reasons to believe that experiments at an energy of the order of a few Terra electron volts (TeV) would bring further progress. The HEP community expects the three TeV colliders (the $p\bar{p}$ Tevatron in USA, the pp collider LHC which has started its journey now and the International Linear electron-positron Collider (ILC) which is now under planning) to help us see the way ahead. Due to the higher energy of the LHC than the Tevatron, at present all the particle physicists look to the LHC to provide the final clinching evidence for the SM and give at least a glimpse of the physics beyond the SM (BSM), which all of them believe, must exist at around the TeV scale.

2.2 Cosmic Connections

Very interestingly the fundamental laws of particle interactions operating at the ‘heart of the matter’ at ‘femto’ meter scales (or smaller) that the particle physicists have been studying, have implications for issues cosmological in nature, concerning the universe, as it was at the beginning and what it is now. The formation of protons/neutrons in the early Universe (Nucleosynthesis), the observed abundances of various elements such as He, Li etc. in the Universe, can now be understood in terms of known physics of these interactions and experiments performed in terrestrial environment and laboratories. However, it is clear now that there are some very basic features of our universe that seem to indicate existence of particles outside the list given in the Tables 1 and 2 of Box-I. Among these are the following facts: 1) The fundamental particles listed in the Tables 1,2 of Box-I constitute only 4% of the total visible matter in the Universe and 23% of the matter in the Universe that is is ‘invisible’(so called Dark Matter,DM) does not consist of particles of the SM, 2)Among the particle content of the Universe, we see only matter particles and virtually no antimatter particles. To be precise the difference between

the number of baryons and anti-baryons normalised to the total number of photons, $\frac{N_B - N_{\bar{B}}}{N_\gamma} \sim 10^{-7}$, and 3) The universe seems to be continuously accelerating. The source of this acceleration is again not found among the known matter/interactions and seems to indicate an unknown form of ‘energy’ (hence called ‘dark energy’) which forms about 73% of the total mass/energy content of the Universe. All these indicate very clearly existence of physics beyond what is in the SM.

What is even more interesting is that possible candidates which can throw light and/or provide solution to these issues, also exist very ‘naturally’ in almost all the ideas of BSM physics that particle physicists have putting forward for an entirely different reason, viz., to remove some of the theoretical shortcomings of the currently accepted description of the SM. But no one idea separates itself completely from the crowd. Experiments are the ultimate Jury which would choose between these different ideas. At the LHC, in addition to hunting for the Higgs boson, the last piece of the SM puzzle, it may be possible to create some of the particles which make up about 23% of the total matter in the universe, the dark matter that is ‘invisible’ to light; or probe the physics that makes the universe of today contain much more ‘matter’ than anti-matter. The LHC can probe this synergy between the world at the femtoscale and the physics of the entire universe and provide answers to some very basic question about nature of things! This should clearly show that the ‘stakes’ in these collider experiments are really high!!

2.3 Accelerators & particle colliders: journey unto LHC

To understand the unique role particle physicists expect the LHC to play, it is a good idea to briefly look into the history of particle accelerators. These high energy particle accelerators are like microscopes which have allowed us to peer at the ‘heart of matter’. High energy proton and electron beams produced using these accelerators have been used in two different modes: 1) The Fixed Target Machines where e, μ, ν and p, π beams are incident on a stationary target which consists of light or heavy nuclei. 2) Colliders where beams of accelerated particles collide against each other. In the latter class only the e^+, e^-, p and antiproton beams can be made to collide in enough numbers to make the experiments meaningful.

In case of a fixed target machine, for a beam of energy E_b incident on a target of mass M_T , total energy available for new particle production is $E_{cm} = \sqrt{M_T E_b} c$, whereas in the collider environment, specialising to the case where both the beams have particles with same mass and energy, the energy available for particle production is $2E_b$. Recall that mass of a proton, a typical target, is $\sim 1 \text{ GeV}/c^2$. Thus the collider mode is superior for new particle production than the fixed target mode, from the

point of view of energetics, as beam energies approach $\sim \text{GeV}$. For example, a particle called J/Ψ with mass $3.1\text{GeV}/c^2$, now understood to be a bound state of a charm-quark and an anti-charm quark, was produced for the first time in 1974 in an e^+e^- collider called SPEAR at SLAC with a beam energy of 2 GeV, whereas soon after, the same particle was created in a fixed target experiment at the Brookhaven National Laboratory which employed proton beams accelerated to 30 GeV.

But energy is only one consideration. Equally important are the Luminosity \mathcal{L} of collisions, i.e. the number of collisions per unit area, per unit time and the kind of interactions that the colliding particles possess. Colliders became a popular tool only after the accelerator physicists developed better techniques to make intense, well focused beams. In fact the SPEAR collider mentioned above, was one of the early example of a collider experiment. Till then the burden of progress was carried mainly by the fixed target experiments.

Through the early part of these explorations, experiments with beams of higher and higher energy just revealed constituents at smaller and smaller distance scales. After the discovery of the quarks, in 1968, lying at the heart of protons and neutrons, the later increase in energy has brought about production of the force carriers and help develop/test the theory which can describe the interactions among the fundamental constituents. Experiments with different fixed target machines and the colliders together, provided this information.

The colliders which helped particle physicists in this journey can be divided in to three different classes based on colliding particles. The leptonic colliders: 1)electron-positron (e^+e^-) and 2) electron-proton (e^-p) colliders and the hadronic colliders: 3)proton-proton(pp), proton-antiproton ($p\bar{p}$) ones.

The story began with e^+e^- circular machines in the 60's at Frascati(Italy), Novosibirsk(Russia) and Orsay(France). It then proceeded through SPEAR (1973), PEP (1980), SLC(1990) at SLAC, Stanford in USA; DORIS(1973),PETRA(1979) at DESY, Hamburg in Germany; LEP-I(II)(1989) in CERN, Geneva, Switzerland, with the beam energy increasing from a 1.5 GeV at SPEAR to up to (15) 23.4 GeV at PEP (PETRA), 30 GeV for Tristan, 45 GeV for LEP-I, SLC and 104.5 GeV for LEP-II. The SLC was the only 'linear' collider among all these.⁶ Finally the story continues now to a possible International Linear Collider (ILC) or Compact Linear Collider (CLIC). It is not yet clear if and where the last mentioned colliders will be built but feasibility studies for these two already go on.

Next colliders to come into play were the proton-proton (pp) and proton-antiproton ($p\bar{p}$) machines. The PS (proton synchrotron) built more than 50 years ago at CERN (and still working today) fed

⁶ BELLE (KEK: Japan) and BABAR (SLAC: Stanford) are the higher intensity but lower energy, $E_b \sim 4.5\text{GeV}$ machines, carrying on the legacy of DORIS at DESY in Germany and CESR at Cornell in USA. This concerns travel on another front in experimental HEP and not discussed further here.

Period	Type	Energy GeV	Perimeter
1971-1976	pp (ISR) Circular,CERN	32×32	$\sim 7km$
1983-1985	$p\bar{p}$ $Spp\bar{S}$, Circular,CERN	270×270	"
1987–	$p\bar{p}$, Circular, Tevatron, USA	980×980	$\sim 6km$
2009 2010–	LHC, pp ,Circular CERN	1180×1180 3500×3500	$\sim 27km$

Table 1: List of hadronic colliders of interest, two are still in action.

high energy proton beams to the Intersecting Storage Ring (ISR) : world's first pp collider (1971). The story then moved on to the Super Proton Synchrotron to achieve $\bar{p}p$ collisions at the $Spp\bar{S}$ collider at CERN, in 1983. Close on its heels was the Tevatron in USA and now the hadronic machine at the forefront is the pp machine is the LHC.

Interspersed with these pure leptonic and hadronic colliders, was a machine which collided electrons/positrons on proton. This ep collider HERA in Hamburg, Germany, provided invaluable information on the quark and gluon content of the proton, which as we will see below is required to predict what particles the LHC can produce and at what rate.

A list of some of these different leptonic and hadronic colliders, of relevance to the discussion here, is presented in the tables 1 and 2. Due to the differences in the nature of the hadronic and leptonic colliders, they have played very complementary roles in our quest for the fundamental constituents of matter and interactions among them. The hadronic and leptonic colliders have different advantages and disadvantages For e^+e^- colliders the initial beam energy is very accurately known as the colliding particles are the same ones which are being accelerated. For the pp or $p\bar{p}$ machines the colliding particles are composites and at high energies the colliding fundamental particles are the (anti-)quarks, gluons: the partons. From the measurements at HERA and other fixed target machines, it is known that, on the average only 1/6 th energy of the proton is available to the colliding partons. Thus for the same energy of the beams, $E_{cm}(e^+e^-) \sim 6E_{cm}(pp)$. Thus to probe physics at a given energy scale, one needs $pp/p\bar{p}$ colliders, with higher energies than the e^+e^- machines. But then it *is* easier to accelerate the p/\bar{p} to much higher energies. Further for a given beam energies, these hadronic machines can provide a broad range of energies at which collisions between partons can happen. Thus a hadronic machine allows us a broad sweep of energies and one can take a quick/dirty look at the landscape, as

Period	Type	Energy GeV	Perimeter (Circular) Length (Linear)
1973-1983	e^+e^- , Circular SPEAR, USA	1.5×1.5 3.5×3.5	$\sim 0.6km$
1978-1986	e^+e^- , Circular PETRA, Germany	6.0×6.0 23.4×23.4	$\sim 2.3km$
1990-2007	$e^\pm p$, Circular HERA, Germany	26.5×800	$\sim 6.3km$
1989-2000	e^+e^- , Circular,CERN LEP-I, LEP-II	$\sim 45 \times \sim 45$ 104.5×104.5	$\sim 27km$
1989-1999	e^+e^- , Linear SLC, USA	50×50	$\sim 3.2km$
???	e^+e^- ,ILC,Linear	500×500	30 km
???	e^+e^- , CLIC,Linear	1500×1500	$\sim 20\text{-}40$ km

Table 2: Some of the Leptonic Colliders : past and in planning.

opposed to an e^+e^- machine where for a fixed beam energy the collision energy is fixed too! Hence, traditionally the hadronic machines have been 'discovery' machines and leptonic colliders have been the precision measurement machines. Further, we really need a hadronic machine to study processes initiated by strongly interacting particles: quarks and gluons.

The physics flow among these different machines is very interesting. For example, the studies of ep collisions at the Stanford Linear Accelerator(SLAC) revealed(1968) that the proton is made up of quarks. Further experiments, in the next three decades with μp , νp collisions from Tevatron/CERN and from ep collider HERA, revealed that the proton contains quarks,anti-quarks and gluons (all three collectively called partons); the evidence for the latter being 'indirect'. These experiments further gave extensive information on proton momentum fractions carried by the partons. The pp collider ISR at CERN gave the first evidence of the parton structure of the proton in pp collisions in 1973.

The experimental evidence for the first of the heavy quarks and leptons, the c quark and τ lepton, happened at the e^+e^- collider SPEAR and the fixed target experiment at Brookhaven, in 1974-1975. Both, the existence and the mass of the charm quark was predicted in 1970 based on the EW model of 1964, mentioned earlier. The τ lepton, discovered at SPEAR, came uninvited to the party. However, its presence was soon found to be necessary, from theoretical considerations, in order to match the

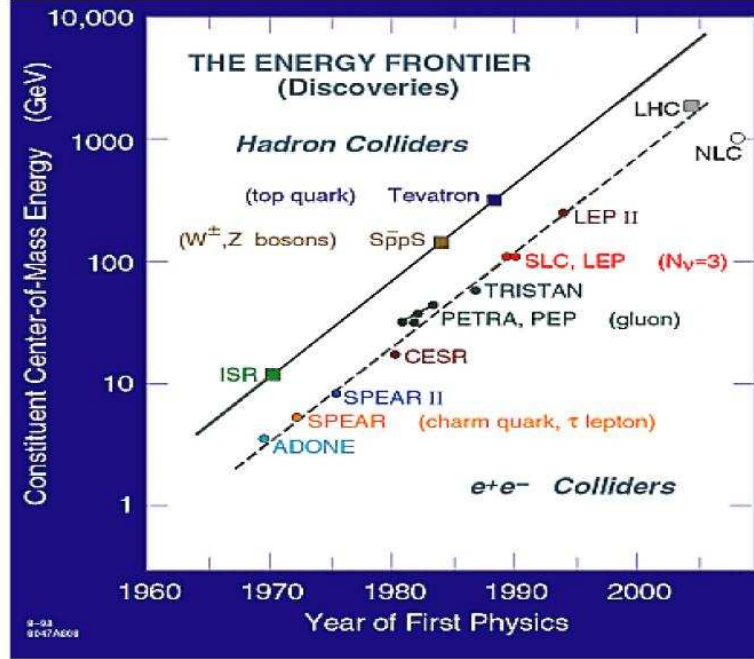


Figure 1: A summary of particle physics discoveries made with different machines

pair of quarks whose presence was predicted from an analysis of the well established phenomenon of CP violation. The two quarks, so predicted, were bottom/beauty(b) and top(t). Out of which the bottom was discovered in a fixed target experiment in 1977, but the discovery of the top quark at the Tevatron had to wait till much later. The ‘direct’ observation of gluons at the e^+e^- collider PETRA in Hamburg, Germany in 1978, was then followed by the direct observation of W and Z at the CERN $p\bar{p}$ collider in 1983. Their mass had been predicted while planning this collider, using the results from the experiments at the lower energy e^+e^- colliders like PEP/PETRA and TRISTAN along with those from the fixed target experiments using ν beams. The first production of a handful (in two digits) of W, Z at UA-1/UA-2 at CERN in 1983 was then followed by production of *millions* of Z at LEP and SLC in 1990-2000.

This is pattern that is repeated time and again. The pp or $p\bar{p}$ machine which is a higher energy, broad band machine makes discoveries, whereas the cleaner environment of e^+e^- colliders allows for precision studies. Thus the lepton and hadron colliders have been alternately taking the role of leading machine, driving the progress of particle physics. The precision measurements at LEP-I and LEP-II, having been complemented by the hadronic collider Tevatron, which discovered the last missing quark, the top quark, now time has come for a higher energy broad band machine.

The information on the main physics discoveries made at different colliders have been summarised in Fig. 1. This shows how the baton for discoveries has moved between different machines and how

the energy frontier has moved. Missing from this figure is the fixed target experiment at SLAC, with electron beams of energy up to 50 GeV which made the discovery of light quarks (u,d) inside proton in 1968 and the fixed target machines which followed it at Fermilab and CERN, with μ, ν beams up to energy 800 GeV, which helped confirm the existence of the strange quark (s).

This shows that the colliders and the fixed target machines have functioned in tandem, revealing layers of substructure of matter and providing information which can be used to elucidate the mathematical description of interactions among the fundamental particles. With the LHC, experimental data using the higher energies reached by the LHC can push knowledge forward, challenging those who seek confirmation of established knowledge, and those who dare to dream beyond the paradigm.

2.4 Precision testing of the SM and pointers to the Higgs hunters

The most important part of the intellectual achievements in the area of particle physics over the past five-six decades, arrived at by using the information from these accelerators and colliders has been the understanding of the three fundamental interactions (shown in Table 2 of Box-I), in terms of exchange of the force carriers among the matter particles. Just like Quantum Mechanics is the correct mathematical framework to describe the phenomena that occur at short distance scales and/or high energies, the mathematical framework which can be used to describe and calculate processes involving creation and annihilation of particles is called Quantum Field Theory (QFT). In fact the description of all the three interactions, strong, electromagnetic and weak, in terms of QFT's with special properties, is the basis of the SM of particle physics. At present a complete mathematical description of all – the low energy and high energy– phenomena in the world of fundamental particles, is possible in this framework.⁷ To get a feel for the level of precision in the experimental measurements and that in the theoretical predictions, I present in Table 3, details of some of the most crucial parameters of the unified theory of electromagnetic and weak interactions (EW theory), which I have taken from Refs. [6, 7]. The level of precision of the EW theory predictions as well as the experimental measurements and the agreement between the two is quite impressive ⁸.

⁷ A lot of these achievements were recognised by a large number of Nobel prizes in Physics in the past fifty years, beginning with the Nobel prize to Feynman, Tomanaga and Schwinger in 1960 and ending with the Nobel prize to Y. Nambu, M. Kobayashi and T. Maskawa in 2008.

⁸In fact the almost complete success of the SM, has led some theorists to wonder whether time has come for a paradigm shift. Further, a quantum theory of the fourth fundamental interaction, the gravitation, seems to lie outside the realm of QFT's describing the three interactions of the SM, the Gauge Field theories. String theorists believe that Quantum Field Theories are sort of a just a 'low energy' paradigm and string theories might be the language to use once you want to include gravitation. Jury is more than out on this point. It is possible that the LHC might tell us

Observable	Experimentally measured value	SM fit
Width of the Z boson: Γ_Z	2.4952 ± 0.0023 GeV	2.4959 GeV
Mass of the W boson: M_W	80.404 ± 0.030 GeV/ c^2	80.376 GeV/ c^2
Mass of the t quark M_t	172.5 ± 2.3 GeV/ c^2	172.9 GeV/ c^2

Table 3: Precision testing of the SM

However, it has to be said that in order that the theoretical computations leading to theory predictions in Table 3 can be performed, in addition to the particles listed in Tables 1,2 of Box-I, one more particle has to exist in the SM. The so called Higgs boson with spin 0, i.e. a particle with no spin degree of freedom. The SM has precise predictions for all the interactions of such a particle with all the other particles. Theoretical predictions for various EW observables do depend on the mass of the Higgs Boson, M_H . The SM predictions shown in Table 3 are calculated using a particular value for M_H . Hence, these precision measurements can in fact be used to derive an ‘indirect experimental’ upper bound on M_H . This can be then further combined with the experimental lower limit from the non-observation of the Higgs boson in all the experiments (at LEP as well as at the Tevatron) up to now. The range of M_H allowed by the current experiments, at 95% c.l., in the SM is $115 < M_H c^2 < 150$ GeV [8]. These limits are of the same order as $M_W/(M_Z) \simeq 84/(91) \text{ GeV}/c^2$. In particle physics parlance one says that the experiments prefer a ‘light’ Higgs boson. Without going into technicalities, let me also mention that in the SM the mass of the Higgs boson is not predicted. But, pure theoretical considerations, making no reference to the above mentioned precision measurements, predict lower and upper limit on its mass.

Thus information available from earlier colliders in fact set the goals for the LHC just like Gamow’s theory predicted goal posts for energy required for radioactivity. The physics flow between different machines and their implications for the LHC are summarised in Fig. 2. Thus we see that results at the current series of machines have always driven the physics at the next generation of machines, giving an indication of the required energy/luminosity. The framework of the SM was abstracted using results from the fixed target ν experiments and from the low energy e^+e^- colliders, DORIS/PEP/PETRA/TRISTAN. In that framework one had a prediction for the masses of W/Z bosons. The $UA-1$ and $UA-2$ experiments (UA standing for Underground Area) measured the masses of these W/Z bosons producing them directly, thus giving the first ‘direct’ confirmation of the SM predictions of these masses. The combined measurements at the LEP-Tevatron, combined with high

that this belief of the string theorists is the truth! Then again it may not!

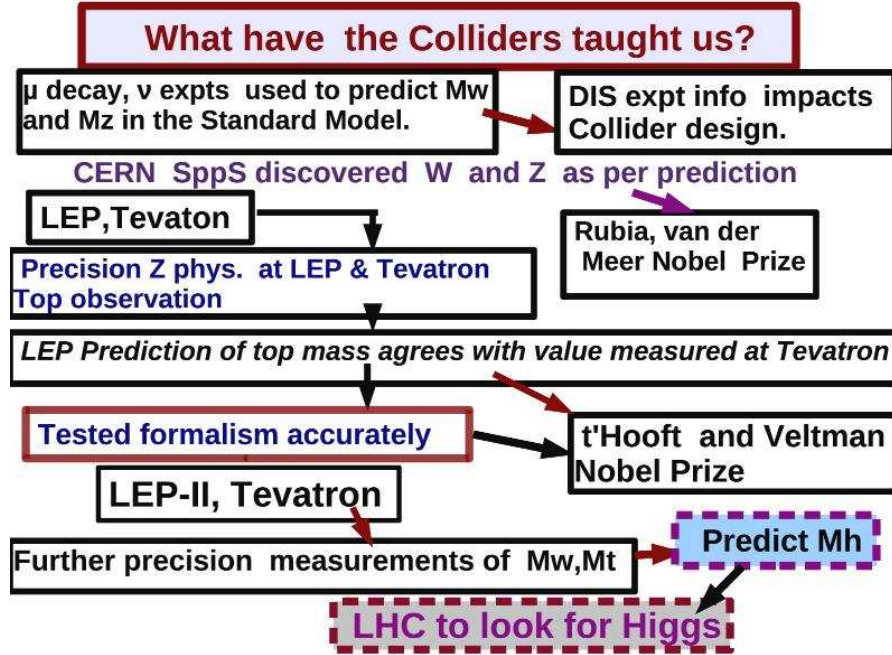


Figure 2: The flow of physics information between different colliders and their impact on design considerations of the colliders.

precision theoretical calculations in the framework of the SM, then led to a prediction of the top mass. The agreement of this predicted value of M_t with the one directly determined at the Tevatron (Table 3), proved the correctness of the SM to a high degree of accuracy. But these highly precise calculations are possible in the SM only if the particle spectrum of Tables 1 & 2, is complemented by a Higgs boson. These precision measurements and calculations, now predict the range in which the M_H value must lie, in the SM. Further the theory itself predicts that M_H should lie in a certain range, SM or BSM, based on purely theoretical arguments. To cover this entire mass range, then a high energy, broad band hadronic machine is needed. The Tevatron does not have enough energy for this purpose. This thus makes the case for the LHC. Of course this will need to be followed by a TeV energy e^+e^- collider, which is already being planned as the LHC is running⁹.

2.5 LHC design

If the SM is correct a light Higgs (ie. with mass comparable to that of the W/Z) **must** be found experimentally. There is strong evidence that the SM is a very good approximation to reality. Right

⁹This too is quite common in HEP. LHC planning was started, when LEP was in construction and the size of the LEP tunnel was decided by keeping in mind that one would want to build a LHC someday in the same tunnel.

now LHC is the only collider which will be able to find a 'light' Higgs boson¹⁰. Even if the SM is not the entire story and hence the Higgs is not in the low-mass range predicted by the SM or is not present at all, the success of the EW theory in explaining the precision measurements indicate that a 'look-alike' of the Higgs boson must be present. The general theoretical bounds on M_H mentioned earlier, encompass those that one computes for the 'look-alike's as well. Hence, observation of the Higgs, measurement of its mass or even the non observation in a given mass range, will shed light on the puzzle of the formulation of a unified theory of electromagnetic and weak interaction (EW theory) and the apparent mystery of the breaking of the corresponding symmetry at low energies [9].

It was clear while planning the LHC that one has to design the machine such that it should be able to probe the issue in a completely model independent fashion. A very general theoretical upper limit on the Higgs mass is about 900 GeV. Even if the SM is not the complete reality, hence no light Higgs boson is found, it would still be possible to unravel the mystery of the EW symmetry breaking by studying effective WW scattering at a total energy of 1 TeV. The choice of energy and luminosity of the LHC was made by by demanding that LHC should be able to cover this eventuality.¹¹

It can be understood somewhat simply as follows. The available knowledge of the quark/gluon

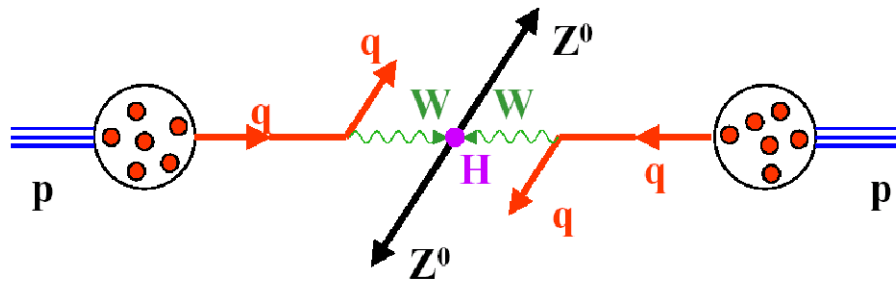


Figure 3: How LHC parameters were decided

content of the proton, indicated that unlike the case of the earlier CERN and FNAL colliders, the physics potential of the machine would be independent of whether one has a pp machine or a $p\bar{p}$ machine. Hence a decision to make the, cheaper and the easier to build , pp machine was taken. Thus the LHC collides proton on protons. As said earlier, the protons are made of quarks and gluons. Hence the collisions at LHC, are effectively collisions among these quarks and gluons. They carry only

¹⁰The Tevatron too can look for a 'light' Higgs but is not so effective in that mass range and it is also not clear how much longer it will run.

¹¹This choice could be made even before the results of the precision measurements at LEP were available to us, because of the general nature of the argument.

a fraction of the energy of the proton. Fig. 3 shows a possible scattering process $WW \rightarrow ZZ$. For the two W's to have a total energy of 1 TeV, each of them must have energy of 0.5 TeV and hence each of the parent quark in the figure must have energy of 1 TeV. From the measured distribution of the momenta of a proton among its quarks, one knows that on the average, the quarks carry about 1/6 th energy of the proton. This means that the protons must have an energy of 6 TeV. Hence one planned on a pp collision energy of 7 TeV on 7 TeV. The total number of pp collisions were decided by using the theoretical estimate for the rate of production of the events $pp \rightarrow WW \rightarrow ZZ$ and demanding that at least 10 events per year be produced. Note how our theoretical knowledge about the SM, has set the bar for the new machine energy and intensity.

3 LHC agenda

3.1 LHC agenda:SM

Thus item number 1 on the LHC agenda is to find the Higgs boson and measure its properties, such as mass and the interaction. The way the LHC has been designed, at its planned energy and luminosity, it will be able to search for the Higgs boson over the entire mass range, allowed on very general principles, irrespective of whether the SM is the whole story or otherwise. Due to the very nature of the hadronic machine, LHC will be able to do the second job of measuring its properties only to a moderate accuracy of about 10 – 20%. A more accurate measurement has to wait for the next generation e^+e^- collider which will have less energy than the LHC, but the measurements will be much cleaner and more importantly the LHC would have indicated to us the Higgs mass and hence the optimal energy to run the machine.

I have focused here on what I believe to be the main reason for planning and executing this mammoth project. Interestingly, however, it transpires that the LHC will also offer almost a direct probe into what went on in the early Universe, in addition to the indirect probes that I have talked about. This will happen in the ‘heavy ion avatar’ of the LHC, where instead of protons, relativistic heavy ions will be colliding against each other. These collisions will recreate energy densities that exist in the early Universe. In the presently accepted description of the early Universe in the Standard Model of Cosmology, the early universe is a hot, radiation dominated plasma, which is an ‘almost’ an ideal gas. This picture, shown in Fig. 4 has been verified up to a temperature of ~ 1 MeV, i.e. the Nucleosynthesis period as mentioned earlier. The period before that is opaque to current astrophysical measurements. In Heavy Ion Collision option one can recreate the transition from the state of a quark-

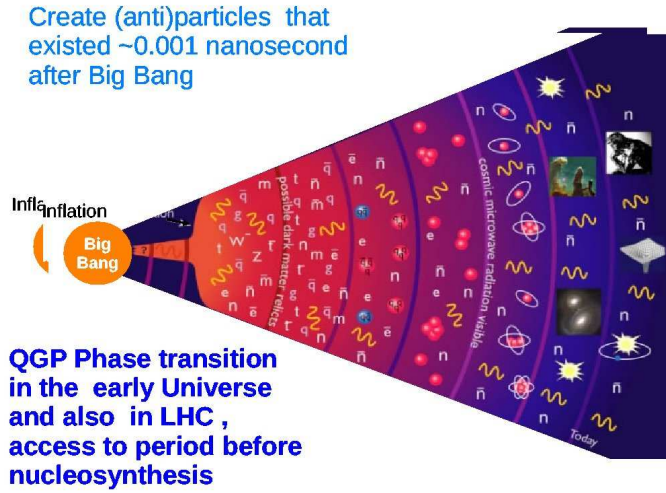


Figure 4: Depiction of different stages in the evolution of the Universe

gluon plasma to the currently known hadrons. Thus the LHC can create a ‘mini-bang’ as opposed to the big-bang which started off our Universe. Study of this transition will also offer a look into the strong interaction dynamics in a region that so far has not been accessible to our experiments and which also poses challenges to the theoretical computation techniques.

The next question to ask is, will it be enough for the particle physicists if a Higgs boson were to be discovered at the LHC with precisely these properties, in precisely this mass range? Will that conclusively complete our understanding of the fundamental interactions among fundamental constituents of all matter? In other words, what is the need for going beyond the standard model, the BSM physics, that I have been mentioning.

3.2 BSM physics

There are a variety of reasons which have prompted particle physicists to look for ideas beyond the SM. Majority of these reasons are aesthetically. But a lot of progress in particle physics (and in fact theoretical physics) has come from looking for elegant explanation of observed physical phenomena and properties. For example, $1/r$ dependence of the Coulomb Potential is due to the ‘zero’ rest mass of the photon and zero rest mass of the photon is due to the fact that Maxwell’s equations have gauge invariance. Thus in this case, the principle of gauge invariance ‘explains’ the experimentally observed nature of Coulomb Potential and zero rest mass of the photon. Similarly, as described in the earlier subsection, the precision testing of the SM, implies that a Higgs OR a look alike must exist and data tell us it must be light! Just like gauge invariance gave an explanation of the power of r in Coulomb’s

Law, we would like to understand why the Higgs is light!! Particularly so because, a quantum field theory of spin 0 particles would predict that the Higgs should be as heavy as can be!!¹² This is one of the ‘theoretical’ reason for expecting BSM physics.

Among the experimental hints for BSM, the most significant is the existence of ‘invisible’ Dark Matter’ (DM) in the universe. Since, this DM can not consist of the particles of the SM, it is a clear indication for BSM physics. It is a matter of enormous interest, that almost all the BSM physics scenarios, ‘naturally’ have a particle that could be the DM in the Universe.

Second experimental hint of BSM physics is the nonzero, tiny mass of the neutrinos. It is now firmly established that neutrinos have tiny, nonzero masses *and* the masses of the fermions have a huge hierarchy. For example the mass of neutrinos is smaller than $1\text{eV}/c^2$ and mass of the top quark is $\sim 175 \times 10^9 \text{eV}/c^2$. In the SM all these masses are just arbitrary parameters. A natural question that has been asked by particle theorists, is whether we can have a fundamental understanding of why they have the values they have? Such questions might sound esoteric, but a lot of progress in science actually has come from asking such questions. Neutrino masses are especially tiny and being neutral, it is possible to have elegant mechanism for generating these ‘small’ masses almost ‘naturally’ in some BSM formulations.

Further, unification of all interactions into one master interaction is a dream which even Einstein had had. At first level, unification of weak and electromagnetic interaction in a single Electroweak interaction, has been observed. All the three interactions do not unify at a given scale if there are no more fundamental particles in addition to those in the SM, whereas such a unification is possible in BSM scenarios. This is one more ‘indication’ of BSM physics. It may be added at this point, that almost all the models which attempt to explain the observed pattern of fermion masses quite often use the framework where the interactions do unify at a high energy scale. Such theories also have mechanisms which can explain the observed matter- antimatter asymmetry in the universe or a candidate for dark matter, almost automatically.

It is worth observing that that both the experimental and theoretical limits on the Higgs boson mass can depend on the (non)existence of the BSM physics and its energy scale, if it should exist. Hence observation of the Higgs and a measurement of its mass can tell us a lot about the energy scale and nature of BSM physics that might exist. This is like trying to decipher the nature of the animal being tracked from its footprints. A brief discussion of some of the theoretical options for the BSM physics that have been proposed is given in Box-II.

¹²If one likes one can interpret the direct/indirect experimental indications for a ‘small’ higgs boson mass as a ‘disagreement’ with the SM.

3.3 LHC agenda: BSM

It should be clear from all these discussions that the the job of the LHC is not finished even when it finds a light Higgs boson. If it is indeed in the mass range that the earlier collider experiments have indicated, the theory must then explain why it is light! Different explanations of why the Higgs is light imply new symmetries, new particles exactly at the TeV scale which should be observed at the LHC. So if a light Higgs boson is found the next item one on LHC phenomenology agenda is to infer which one of the many explanations (if any) is right.

A natural question is what if we don't find it? It would mean that there is an alternate to EW symmetry breaking which passes the challenge posed by the precision tests as comprehensively as the SM does. Then the LHC agenda item is to check which one of these alternates, if any, is correct ! So one of the big area of phenomenological research has been how to delineate different BSM ideas from each other [10] at the LHC.

From the discussions of the different BSM physics scenarios it is clear that the hunt for these BSM scenarios may in fact help us explore further at the heart of matter and probe the structure of space time. Most of the time due to the very nature of these BSM ideas, they have implications for the early Universe and hence this is an opportunity to test some of the ideas of the Standard Model of Cosmology at the LHC.

I reproduce below a list of objectives that have been set out in a road map of particle physics for the next decades by the world community.

- Are there undiscovered principles of nature: New symmetries, new physical laws?
- Are there extra dimensions of space?
- Do all the forces become one?
- Why are there so many kinds of particles?
- What is dark matter? How can we make it in the laboratory?
- What are neutrinos telling us?
- How did the universe come to be?
- What happened to the antimatter?
- How can we solve the mystery of dark energy?

Apart from the last point in this list, we expect the LHC to shed light on almost all the points. That is the reason LHC is the watershed experiment in Particle Physics. All of us are looking to it to point the way ahead.!

4 LHC machine and physics: time line

4.1 LHC machine: accident and repairs

Even by the standards of HEP laboratories designing and building the Large Hadron Collider was a challenging exercise. As said above, LHC was conceived in 1980s and the planning began already in 1989. The tunnel which houses the LHC now, was built between 1983-1988 and was home to the LEP experiment till 2000. CERN Council approved construction in 1994. Limiting oneself to the use of the LEP tunnel meant that there was an upper limit of 7 TeV to the energy to which the protons could be accelerated¹³. Hence the LHC had to plan on larger luminosity. This meant smaller bunches, higher magnetic fields and packing more particles per bunch. The LHC builders then decided to use new methods for acceleration. They also decided to use a very innovative idea where the beams would circulate in two separate rings just above one another. For e^+e^- or $p\bar{p}$, the same magnetic field automatically suffices to steer the two bunches in opposite directions. That is not the case when both colliding particles have the same charge as they do for the LHC. All this was not just technologically challenging, but also expensive. The decision was then taken by the CERN Council to build it in two stages. In the meanwhile plans for the SSC were abandoned. From 1995 onwards, countries which were not members of CERN, viz., Japan, USA, Canada, India and Russia, promised support to the LHC machine and decision was taken to do it in one go. While the Indian HEP community had participated in building detectors and doing experiments at the earlier fixed target and collider facilities, this was the first instance where India participated in the building of the machine itself.

Given the ring size and the energy to which particles needed to be accelerated, meant that one needed to have higher magnetic fields of about 8 Tesla. This in turn meant that the magnets had to be cooled down to 1.9° K. Contrast this with the other superconducting collider Tevatron where this temperature is about 5.2° K and the magnetic fields required about a factor two smaller. The magnetic fields required at the LHC are also higher than the one used at the old SPS, by about a factor 5. Not

¹³To reach the same physics goal of being able to hunt for the Higgs up to the general upper limit of about 900 GeV, the then under planning and later canceled, Superconducting Super Collider (SSC) project in USA, was supposed to accelerate the beams to an energy of 20 TeV in a much bigger tunnel.



Figure 5: The quadrupole-dipole connection: undamaged and damaged in the left and right panel respectively.

just that, 10-12 Tesla is about the upper limit at which these Niobium-Titanium accelerator magnets can function, still remaining superconducting. All this should give a flavour of the engineering and technological improvements that were required for the LHC. The most crucial piece of the machinery for the LHC are the 1232 dipole magnets, each weighing 34000 Tonnes and costing about 0.5M CHF each.

Before the start up of September 2008, the energy goal was already lowered from the initial 7 TeV to 5 TeV, with plans to raise the energy afterwards. Its start up in September 2008, came to an abrupt end during a test of *the* one sector which had not been tested before for the full current corresponding to an energy of 5 TeV. Most likely, an electrical arc developed and it punctured the Helium enclosure. Large amounts of Helium gas were released into the insulating vacuum of the cryostat and a large pressure wave traveled along the accelerator both ways. The pressure was too large to handle for the pressure release systems which had been put in place. One of the quadrupole-dipole connection, before and after the incident is shown in Fig. 5. The severity of the accident becomes obvious when one recalls how heavy these magnets are. Thirty nine of the 1232 dipole magnets and 16 of the quadrupole magnets had to be replaced, vacuum tubes had to be cleaned, new pressure release systems as well more diagnostic methods to avoid a similar accident again, had to be installed. All these repairs were completed by fall 2009. A large amount of time is required to cool the machine to the low temperatures, which has to be done gradually. Finally by the end of the November 2009, the machine was ready to go again and as said in the introduction the collisions have taken place. However, it is noticed that

the Superconducting magnets need to be ‘trained’ to carry higher currents and hence the ramping of the energy will now be gradual. Initially now the machine will run only with beams of 3.5 TeV each (exactly half the design energy and less than the 5 TeV which was planned for the 2009 run). It is now proposed that the machine will run at this energy till end of 2011 and then again there will be a major shutdown to ramp up the energy up to 6.5 to 7 TeV per beam, (the 7 TeV looking a bit difficult to reach as per present studies), as well as an increase towards the ultimate design luminosity, of $10^{34}cm^{-2}sec^{-1}$. (This was the number that I had used in explaining how the LHC design energy was decided.) Now it is foreseen that the design energy and luminosity, will be only reached, after a period of about two years, as per current plan.

It should be mentioned that for this low energy run, a reduced luminosity of $10^{32}cm^{-2}sec^{-1}$ is foreseen. However, as I write these lines, only a luminosity of $10^{30}cm^{-2}sec^{-1}$ has been achieved. This is partially because these big machines are like a delicate musical instrument which needs to be finely tuned. For example, when larger number of bunches are injected, to increase the luminosity, the bunch-bunch interactions can destabilise the beam. These interactions are understood, in principle, and included in the designs; still fine adjustments to the beam parameters are required to get rid of these effects while the machine is running. Right now accelerator experts are working on it, alternating their work with giving the beam for actual physics run to the experimental physicists. The bunches with the LHC design intensity (i.e. 1.15×10^{11} p per bunch), have already been successfully injected. To increase the luminosity one would need to increase the number of bunches. After beginning with one bunch, they had gone up to 13 bunches with $\sim 10^{10}$ ppb and 7 bunches for the $\sim 10^{11}$ ppb. The goal is to reach 2808 bunches. The possible time line of the expected physics results will in fact depend very much on the success of this tuning procedure. In the following I shall assume that in a few months at least a luminosity of few times $10^{31}cm^{-2}sec^{-1}$ will be achieved.

4.2 Possible time line of Physics results

As mentioned already, an evaluation of how well the mammoth detectors can achieve their goals, requires precise theoretical predictions. A large number of very detailed analyses, with the combined participation of the theorists and experimentalists alike were done to analyse the physics prospects of the LHC [11]. Most of the very detailed analyses used the nominal LHC energy of 14 TeV and the nominal luminosity of $10^{33} - 10^{34}cm^{-2}sec^{-1}$ in the first year. The value at the lower end means that there will be 10 events per year ($\sim 10^7$ sec = 150 running days in a year), per *fb* cross-section. This is termed as luminosity of 10 fb^{-1} per year. The number on the right hand side indicates the number of

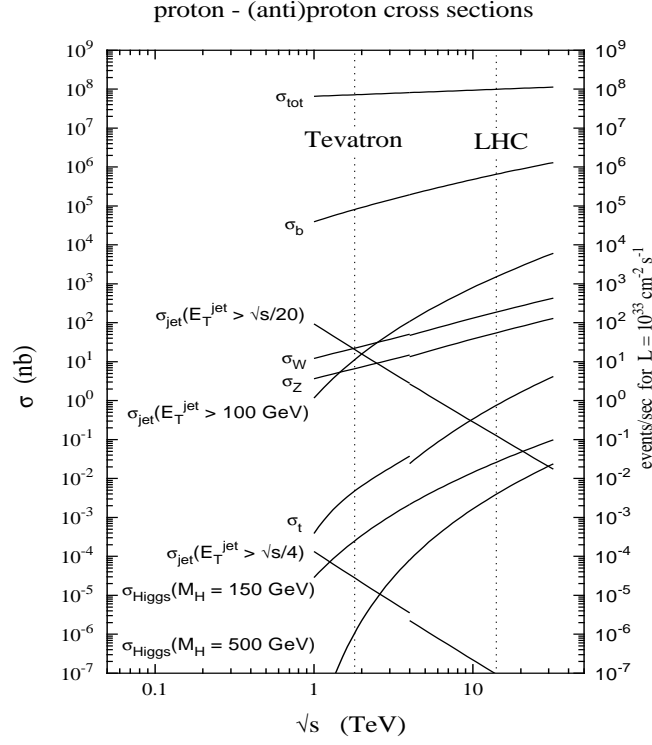


Figure 6: The cross-sections for various processes expected at the LHC.

events for a particular process for the lower value of the nominal luminosity of $10 fb^{-1}$ or equivalently $10^{33} cm^{-2} sec^{-1}$.

One can see, from the figure that even at the high energy and luminosity, finding a Higgs with the lowest mass that is allowed for it by experimental constraints is not an easy job. For example, for a Higgs with $M_H c^2 = 150$ GeV, one expects only a handful of events where a Higgs boson is produced.¹⁴ One can see that the cross-sections for different processes fall with varying factors as the collision energy is lowered. However, just a simple scaling by this factor is not enough to judge the change in sensitivity due to the present reduction in the energy and luminosity, as the background processes in general have a slower fall off with the reduction in energy than the signal process of interest.

So in the short run, ie. in the next two years, with the machine delivering at the most, a luminosity of $10^{32} cm^{-2} sec^{-1}$, one is not likely to see a signal for the SM Higgs boson, if it has mass in the range indicated by the current experimental constraints¹⁵ There is a possibility of detecting the Higgs,

¹⁴Further, when one multiplies it with the probability that it will give rise to an event that can be distinguished from the background the number falls to may be an event or less a day.

¹⁵It is interesting that already with the luminosity of $\sim 50 nb^{-1}$ that has been delivered the LHC could already have produced one event of the type $p + p \rightarrow h + X \rightarrow b + \bar{b} + X$, if its mass is around 120 GeV. Unfortunately, the background

even for this 'low' luminosity, if its mass is around 160–165 GeV, but the Tevatron data has ruled out existence of a SM Higgs in this mass range at 95% c.l. However, due to limited statistics and the theoretical uncertainty in the prediction of cross-section, this limit has to be taken with some reservation [12].

Luckily, the production cross-section for the different varieties of new particles that are expected in the different BSM scenarios, go down much more slowly with energy. For example, even with this lower luminosity and energy, the LHC has a chance to 'discover' Supersymmetry if the masses of the strongly interacting super-particles are less than 800 GeV, about twice the current limits from the Tevatron Collider. So clearly the possibilities for the BSM physics are quite tantalising even at the lower energy/lower luminosity LHC. Thus the search for the Dark Matter in the Universe at the LHC can already happen in these two years. One good news is that the detectors are working perfectly and are able to remeasure the SM processes well, to calibrate the SM backgrounds to the new physics searches using the experimental results themselves.

The studies for the Quark Gluon Plasma formation (and hence recreating the situations in the early Universe) should not be affected in a major way due to the energy reduction. Thus the heavy ion program and the LHC_b program (to study the issue of CP violation and flavour physics at the LHC), also should not be affected in a big way due to the reduced LHC conditions.

Whether the Higgs field is an elementary particle as in the SM or a 'look-like' which may not be elementary; whether there is only one or there are more of them : elementary or composite; one thing is for sure, the problem of reconciling a left handed world with massive matter particles, requires existence of a new phenomenon and the LHC has been designed to solve this enigma. However, we need to be patient, given the complexity of the problem, the rarity of the phenomena that we need to analyse to get the answers, along with the reduced energy and luminosity. Several years of data-taking and analysis will be needed to sort out the puzzle.

It is heartening that Indian experimental groups have been contributing to building the detectors and doing experiments with the pp as well as the heavy ion collisions. Further, the Indian theoretical physics community is also involved in a big way in LHC physics, be it the SM, BSM physics in pp collisions with the CMS/ATLAS detector, or the B-physics in LHC_b or the physics of the QGP in the heavy ion mode.

After a shutdown that is planned at the end of 2011, the machine physicists will work on getting to the higher energy. Once that energy is reached, LHC should be able to full fill its promise of hunting

is too huge in this channel and the ONLY promising channel for such a light Higgs, is when the h decays into $\gamma\gamma$ final state and such events will happen at a rate 1000 times smaller.

for the Higgs over the entire mass range allowed for it theoretically, which is indeed the ‘Raison de tré’ of this machine. So in short this complicated exercise is sure to keep the particle physics community busy for a decade or two and yield answers to some of the basic questions about the very fabric of space and time and the Universe we all live in, as the particle physicists travel in this ‘terra incognita’. In all probability it will throw up some unexpected results, which in fact will point the way ahead in this journey towards truth. Exciting times are ahead for sure !

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BOX1: Some relevant facts about the Standard Model (SM) of particle physics.

In the past 50-60 years particle physicists have successfully arrived at a description of elementary constituents of matter the matter particles quarks and leptons, all with spin 1/2, summarised in Table 4,

Quarks	Leptons
$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$ <p style="text-align: center;">× 3 colours</p>	$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$ <p style="text-align: center;">‘colourless Leptons’</p>
$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} u \\ d \end{pmatrix}$ <p style="text-align: center;"><i>etc.</i></p> <p style="text-align: center;">+anti-quarks</p>	<p style="text-align: center;">‘colourless Leptons’</p> <p style="text-align: center;">+ anti-leptons</p>

Table 4: The fundamental constituents of matter.

interacting with each other via the three basic interactions shown in Table 5 ¹⁶. The quarks possess the so called ”colour’ charge and hence a given quark pair appears three times in the counting in three different colours. The quarks u,d (up,down) make the normal matter (which is colourless) like protons/neutrons and these with the lightest charged lepton, the electron in fact make up atoms/molecules etc. All the remaining fundamental particles: the quarks strange(s), charm (c), beauty (b) and top(t), the charged leptons μ, τ and the neutral leptons: neutrinos (ν ’s), are produced either in decays of nuclei or unstable particles and/or in high energy processes. The lighter quarks (u,d,s) manifest themselves only as bound states like protons, pions and kaons. The heavier quarks and charged leptons are all short lived, with life times of the order of 10^{-6} sec. or lower. The neutrinos have only weak interactions, whereas the colourless charged leptons have weak and electromagnetic interactions and the coloured

¹⁶The gravitational interaction is not included since we do not have a similar level of theoretical description of this interaction in terms of a force carrier.

Interaction	Description	Carrier Particle
Electromagnetic	Long-range charged quarks and leptons.	Photon γ
Weak	Short-range between quarks and leptons.	W/Z Bosons
Strong	Short-range Only quarks	Gluons g

Table 5: Basic forces in Nature and their carriers.

quarks feel all the three interactions. The properties of all the particles, the constituent matter particles and the force carriers, have been measured to a high degree of accuracy and the periodic table for particle physics is *almost* complete. Hence, admittedly it is time to see if there is an underlying theory which explains the patterns in these properties such as their masses and electromagnetic charge etc. that we observe. To answer such questions one has to go beyond the SM.

Tables 4 and 5 do not contain one particle in the SM, viz. the Higgs boson, which is neither a fundamental constituent of matter nor a force carrier. It was introduced to understand a particular mystery of weak interactions. These seem to treat the left handed matter particles, quark and leptons whose direction of the spin is opposite to the direction of motion, differently, from those which are right handed *i.e.* those for which these two directions are parallel to each other. For a particle with a nonzero rest mass, a left handed state can be seen as a right handed state by simply going to a frame which is moving faster than the particle. Thus the weak interactions then will depend on the frame of reference. This would be in conflict with Einstein's theory of relativity. A theory with a Higgs boson does not suffer from this problem. This boson is named after one of the scientists who originally proposed this, more than 45 years ago. It is thought to have no electric charge, and no spin. As for its mass, unsuccessful searches at the LEP collider and the Tevatron collider, along with precise measurements of the weak interactions put $M_H c^2$ to be in the range of 114 to ~ 150 GeV, the result being strictly true within the SM.

BOX2: A very brief summary of the theoretical proposals for BSM physics.

A number of different ideas for BSM physics have been put forward through the decades. They can be roughly classified into three classes: 1) The first class of models tries to keep the Higgs mass small by introduction of an additional symmetry. One of the most elegant ways to do this is via Supersymmetry. This is a symmetry between fermions (spin $1/2$ particles) and bosons (integral spin particles). This implies that there exist supersymmetric partners of all the SM particles. In this case, there exist host of new particles which we should see at the colliders, particularly at the LHC [1] and it also has a DM candidate particle, the neutralino. The mass and interactions expected for the neutralino in SUSY models, falls in the range required to explain its abundance in the Universe today. Another class of models, called Little Higgs Models, in fact tries to use the lessons learned from the SIB in the case of the SM, to keep the Higgs light. In this case also, there exist many additional fermions, gauge bosons in the theory at the TeV scale, their interaction patterns being different than in the case of SUSY.

2) The second class of models obviate the high energy scales which cause the theoretical predictions of corrections to Higgs mass to become large. These models are much more radical in that, in general they postulate behaviour of space and time which is completely different than what we understand and involve one or more extra dimensions of space, which are compactified. These extra dimensions may even have warped geometry. In this case, the Higgs remains light, it may or may not be a fundamental particle. Gravity is free to propagate in the extra dimensions. Gravity in principle is as strong as the Electroweak interaction, but appears weak in our world. TeV-scale experiments probe the ‘strong gravity sector. Thus there is again new physics at a TeV scale. Some of these ideas also make conceptual contact with quantum theory of gravitation and sometimes even have statements to make about early universe cosmology. It is an exciting possibility, where the TeV energy colliders can probe structure of space time. Even more interesting, string theory has now begun to make some statements about such models. In this case, the Higgs remains light, it may or may not be a fundamental particle.

3) Then there are extremely daring ideas which try to do without any Higgs like particle; fundamental or composite.

It is fair to say that in general all the models in class 2 and 3 above have more trouble satisfying the constraints coming from the precision measurements than supersymmetry. On the other hand, not finding supersymmetric particles so far, has created another set of ‘theoretical’ problems for supersymmetric theories which I will not go into here.

References

- [1] See, for example, See e.g. M. Drees, R.M. Godbole and P. Roy, *Theory and phenomenology of sparticles*, World Scientific, 2005; H. Baer and X. Tata, “*Weak scale Supersymmetry: From superfields to scattering events*,” Cambridge, UK: Univ. Pr. (2006) .